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PROJECT TECHNICAL REPORT
TASK ASPO 57

LM SOIL EROSION STUDIES
FINAL REPORT

NAS 9-4810 31 JANUARY 1968

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Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Prepared by
R. E. Hutton

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To:

TRW
SYSTEMS GROUP

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Approved by

V. R. Widerquist, Manager
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Project

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1. SUMMARY

Conclusions have been formulated concerning the potential landing hazards posed by soil erosion resulting from the interaction of the LM descent engine plume and lunar surface. Potential hazards of concern are: degradation in landing stability resulting from the formation of large erosion craters in the lunar surface; degradation of visibility because of the deposition of dust on the astronaut's window; degradation in radar visibility because of excessive dust and debris; and damage to LM structural elements by debris ejected from erosion craters. The conclusions presented here are drawn from the results of theoretical studies supported by earth based experiments, and experiments conducted by Surveyor spacecraft on the lunar surface.

It is concluded that soil erosion during LM lunar landing will be small and

- The erosion crater will be less than 0.6 ft deep and will not cause a significant degradation in landing stability even if a footpad landed in the crater.
- Visual degradation should not be a hazard since erosion does not occur until shortly before touchdown. The deposition of dust on Surveyor spacecraft has been small, if any, and there is no evidence indicating that a large dust deposition may occur on the astronaut's window.
- Soil erosion will not occur until the LM is about 10 ft above the lunar surface and, therefore, will not effect radar performance.
- Some debris may impact the lower portions of LM primarily in the region of the descent engine exhaust nozzle or the landing legs. Estimates of the momentum of debris having nearly a vertical trajectory are 1.4×10^{-7} lb-sec based on conservative theoretical predictions and 1.5×10^{-10} lb-sec based on earth based tests. Lunar based tests have given no indication of significant debris ejected with nearly vertical trajectories. Little material has been observed on Surveyor spacecraft following the soil erosion experiments. Estimates of the momentum of debris having low trajectory angles (about 25° or less) are 0.0042 lb-sec from earth based experiments. This value is based on a measured debris velocity of 22

ft/sec and 1/2-in. diameter particles. On Surveyor VI debris impacted the photometric chart and must have been ejected at a very large angle (larger than 25°). The momentum value of 0.0042 lb-sec serves as an upper bound estimate for this debris. However, it is believed this was an anomalous occurrence on Surveyor VI, most likely associated with the interaction of the three engine plumes. If so, this would not occur with the single engine on LM.

In summary, all evidence to date indicates soil erosion during LM landing should not pose a significant hazard to any portion of the lunar approach and touchdown sequence. These conclusions have relied heavily on data obtained from the lunar surface from various Surveyor spacecraft. Lunar surface mechanical properties data were used in making theoretical predictions of soil erosion during LM landing. Also, these data have allowed an interpretation of soil erosion test results obtained by the Langley Research Center using a model of the LM descent engine in erosion experiments conducted on a variety of simulated lunar soils. However, the most convincing data for making an assessment of erosion during LM lunar landing were the erosion results obtained by Surveyors III, V, and VI since these tests were performed on the lunar soil and in the lunar environment at soil loading levels and thrust termination conditions representative of those during LM landing.

This report first discusses general information concerning the interaction of a rocket engine exhaust plume and a soil surface. Then, a summary of the findings from the various investigations that support these conclusions are presented.

2. INTRODUCTION

Earth based tests conducted before the Surveyor lunar missions indicated that three basic types of erosion could occur when rocket gases impinge on a soil surface, each of which had the potential of seriously degrading LM landing performance. These types are often referred to as viscous erosion, explosive cratering, and diffused gas eruption.

Viscous erosion (References 1, 2, and 3) is a surface erosion caused by shearing forces acting on the soil developed as the gas flows over the surface. These viscous shearing forces dislodge soil particles from the surface, which then become entrained in the flowing gas. Gravity forces eventually cause the entrained soil particles to fall back to the surface. This type of erosion is similar to that caused by the wind as it blows over a sandy area. In the case of a rocket engine oriented perpendicular to the surface, the gas is turned by the surface and flows radially outward away from the stagnation point (the point where the jet centerline intersects the soil surface). The resulting erosion crater often has the shape of the lower half of a toroid centered about the stagnation point.

Explosive cratering (Reference 4) is a type of cratering caused by the normal forces acting on the soil surface due to the gas static pressure. The crater formation process occurs a few milliseconds after the impingement of the gases and is believed to result from a shear type of failure within the soil. Such a failure is similar to that observed when the loads on structural foundations exceed the bearing capacity of the soil.

Diffused gas eruption, unlike the other two, is a cratering process that occurs after thrust termination. It is initiated by an increase in subsurface pressure through a diffusion of rocket gases into the porous soil during engine firing. Then with thrust termination and the rapid decrease of surface pressure, the unbalanced pressure forces cause an upward displacement of the pressurized soil and a rupture of the surface.

Before Surveyors landed on the lunar surface, estimates of lunar soil mechanical properties extended over such large ranges that it appeared any one of the three erosion mechanisms could seriously degrade LM landing performance. Surveyors later provided much better estimates of soil properties and, more importantly, performed soil erosion experiments on the lunar surface that simulated LM loading levels and engine shutdown conditions.

3. RESULTS

3.1 EXPLOSIVE CRATERING

The explosive type of soil cratering was observed during experimental studies performed under atmospheric conditions at the Hayes International Corporation (Reference 4). This type of failure was later theoretically investigated in Reference 5 utilizing the lunar soil properties provided by Surveyor I. It was concluded from this investigation that such a failure would not occur during LM landing, because Surveyor I data indicated the lunar soil to have a sufficiently high weight density, internal friction, and cohesion to support the surface pressure loadings developed by the LM Descent Engine. Experimental data also lend support to this conclusion. In erosion experiments conducted in vacuum chambers, which allow the plume to expand in a manner representative of a lunar atmospheric condition, there has not been evidence of an explosive type of cratering. However, the most convincing evidence is that provided during the lunar hop of Surveyor VI. During this experiment the maximum pressure exerted on the lunar surface was twice the maximum anticipated during LM landing and there was no evidence of explosive cratering. Thus, no evidence of explosive cratering has been observed under LM simulated conditions in vacuum chambers or on the lunar surface; and therefore, it is concluded such an erosion type will not occur and no hazard exists resulting from explosive cratering.

3.2 DIFFUSED GAS ERUPTION

Diffused gas eruption was observed (Reference 5) during tests conducted by the Jet Propulsion Laboratory. In these tests the Surveyor vernier engine was fired in a vacuum chamber and the exhaust gases directed onto a soil believed to be similar to that found at the Surveyor I site. The largest surface eruption occurred in the soil having the smallest particle size (unpacked silty sand). The average particle size on the unpacked silty sand was 0.000197 ft (60 μ), had a particle mass density of about 5 slugs/ft^3, and was nearly cohesionless. The maximum surface pressure was about 1 psi, which is approximately the maximum value to be exerted during LM landing. Following engine cutoff the surface erupted upward about 0.9 ft. If it is assumed that the eruption imparted an initial velocity to dust particles that subsequently caused them to rise 0.9 ft above the surface, then the initial velocity would have been 7.6 ft/sec and the momentum imparted to the particles would have been 1.5×10^{-10} lb-sec.

A theoretical investigation of this phenomena was also performed in Reference 5 for a LM lunar landing. This investigation indicated some eruption could occur; and if it did, the eruption crater would be essentially confined to the region below the nozzle and formed after touchdown. The momentum associated with dust particles striking the lower portions of the LM stage just outboard of the descent engine nozzle was estimated to be 1.4×10^{-7} lb-sec. This estimate was based on a nearly cohesionless soil having a soil particle diameter of 0.02 in. and an upward velocity of 11.4 ft/sec at the time of impact. This particle diameter was believed to be conservative since such a surface eruption was only observed in soils having particle diameters at least an order of magnitude smaller. Theoretical calculations of smooth spherical particles impacting a 1-mil mylar membrane at a value of momentum several orders of magnitude higher than this theoretical value were required before a permanent set was caused in the mylar sheet.

A series of erosion tests conducted by the Langley Research Center on the Apollo RCS Engine (Reference 5), subsequent to the Jet Propulsion Laboratory tests where diffused gas eruption was observed, indicated that such an eruption occurs only rarely. The only LRC test in which it was clearly observed was a test on pumice.

The diffused gas eruption phenomena was investigated by Surveyor V on the lunar surface (Reference 6). In this test the vernier engines were fired for about 0.5 sec at a thrust level less than the Surveyor lunar weight. This test was believed to have been representative of thrust termination during LM landing. The small crescent shaped crater formed was attributed to gas diffusion. When the observed crater was scaled to LM conditions, the resulting crater was 4.2 ft in diameter and 0.29 ft deep.

A small amount of soil debris was deposited on the top of the electronic compartments; however, no change was detected in the thermal characteristics. In fact, no degradation was detected in any functional capability of the spacecraft as a result of vernier engine firing. A change of reflectivity of the smooth vertical surface on the alpha-scattering sensor head was detected, thereby indicating some debris may have been deposited on the surface. This instrument was resting on the surface and should have been subjected to the direct blast of the gases flowing along the surface.

The erosion experiment on Surveyor VI did not simulate a diffused gas soil eruption condition during LM lunar landing, because the spacecraft lifted from the surface and produced a slower reduction in surface pressure than will occur during LM engine cutoff. During the Surveyor VI lunar hop, engine cutoff occurred at a nozzle height in which the surface pressure was negligible. Little or no lunar debris was deposited on the spacecraft.

On the basis of these observations and theoretical investigations it must be concluded that some debris may impact LM during lunar landing. However, the evidence available indicates the amount of debris should be small and the potential hazards to landing minimal.

3.3 VISCOUS EROSION

Viscous erosion has been a subject of experimental and theoretical investigation for several years by the Langley Research Center. One experimental investigation was made using a model of the LM descent engine. These tests were conducted in the vacuum sphere for a range of LM thrusts and descent speeds on several simulated lunar soils. The erosion data obtained in these tests were used in Reference 8 to establish values of nondimensional coefficients in a modification of the viscous erosion theory advanced in References 1 and 2. The procedure was then verified by a comparison of theoretical predictions and erosion test results obtained from an earlier set of tests conducted by LRC.

After Surveyor I landed and more reliable estimates of the lunar soil mechanical properties were available, theoretical computations of soil erosion during LM landing were performed in Reference 8. Also, a knowledge of the lunar surface properties made it possible to identify which of the LM model soil erosion tests conducted by LRC was most representative of LM lunar landing. Both the theoretical predictions and LM model test data indicated viscous erosion would not constitute a landing stability hazard for LM. Taking the worst combination of soil properties given by Surveyor I data, it was found in Reference 8 that the depth of the viscous erosion crater would be 0.955 ft, while based on nominal values it would be 0.175 ft. Also in Reference 8 it was found that the LM scaled tests indicated the erosion depth would be no greater than 0.25 ft.

A soil erosion experiment was inadvertently performed by Surveyor III during touchdown because the vernier engines failed to shut down at the planned 13-ft height. This led to three separate touchdowns. Because of an existing horizontal velocity, the touchdown points were laterally displaced about 66 ft between the first and second touchdown and about 36 ft between the second and third touchdown. Engine shutdown occurred sometime between second and third touchdowns. Erosion craters caused by the interaction of the vernier engine exhaust gases and the soil were not clearly identified. A surface irregularity about 3.3 ft long and of shallow depth observed near the second touchdown point may have been due to a vernier engine. Since the erosion data were of questionable validity and subsequent Surveyors provided more reliable soil erosion information, no attempt was made to extrapolate these Surveyor III erosion results to a LM landing condition.

The static vernier engine firing experiment on Surveyor V (Reference 6) was conducted to investigate diffused gas eruption. The test consisted of about a 0.5 sec firing at a thrust level less than the spacecraft's lunar weight. A crescent shaped erosion crater was observed under Vernier Engine 3 that was about 8 in. in diameter and 0.5 in. deep. It was believed that the crater was formed primarily by diffused gas eruption. The maximum surface pressure developed by Surveyor was about one-half the maximum pressure loading anticipated during LM landing. Under the assumption the crater was formed entirely by diffused gas eruption, a conservative estimate of the corresponding eruption crater during LM landing was estimated to a 4.2 ft in diameter and 0.29 ft deep, as was already mentioned. While, under the assumption the observed crater was caused entirely by viscous erosion, a conservative estimate of the corresponding viscous erosion crater formed during LM landing was a crater 0.6 ft deep.

A lunar translational maneuver was performed on Surveyor VI in which the spacecraft was moved laterally about 8 ft. This experiment provided valuable viscous erosion information for LM. During the lunar hop the vernier engines loaded the soil surface to maximum pressure levels about twice the maximum anticipated during LM landing. No diffused gas eruption of the surface nor explosive cratering was detected. Viscous erosion did take place, but it was small and was certainly less than 1 in. in depth. Although the maximum loading level was higher than the maximum loading level during LM landing, the loading impulse is larger for LM because of the longer loading period existing during the slow descent manual mode. In Reference 7 the Surveyor VI results were scaled to LM conditions with the result that the maximum erosion crater depth would be less than 0.1 ft.

Estimates of the momentum associated with the debris dislodged by viscous action can be made from the earth based Surveyor vernier engine tests discussed in Reference 5 or the lunar test discussed in Reference 7. In Reference 7 it was estimated that the debris dislodged from the surface had a velocity in excess of 7 ft/sec. In Reference 5 the velocities of some particles having diameters from 0.25 to 0.50 in. were measured to be from 12 to 22 ft/sec. The particle mass density of these soil particles was about 5 slugs/ft^3. For the largest diameter particles and largest velocity, the momentum imparted to the soil particles was 0.0042 lb-sec. This serves as an estimate of the momentum imparted to particles of the size which may have impacted the photometric target during the Surveyor VI lunar hop (Reference 6). The angle the soil particle departed from the surface in the earth based tests discussed in Reference 5 was estimated to be about 25° with the horizontal surface.

4. CONCLUSIONS

Theoretical predictions and LM scaled erosion tests indicate some soil erosion may occur when LM reaches a height of about 10 ft above the lunar surface. Viscous erosion may occur during powered descent and diffused gas eruption may occur after thrust termination. Both earth and lunar based tests and theory indicate that surface loadings during LM landing will not be high enough to cause a surface cratering of the explosive type.

The maximum soil erosion crater depth predicted during LM landing is obtained by scaling Surveyor V erosion data to LM conditions under the assumption the observed erosion was caused by viscous erosion. The corresponding erosion crater for LM would be 0.6 ft deep for the slow descent, manual mode. Scaling Surveyor V data to LM conditions under the assumption that the observed crater was formed by a diffused gas eruption of the surface indicates the eruption crater would be 0.29 ft deep. When Surveyor VI erosion data were scaled to LM landing conditions, the erosion depth was only 0.1 ft. Since LM was designed to land on a lunar surface containing 1-ft depressions or protuberances, an erosion crater 0.6 ft deep would not constitute a landing hazard even if a footpad landed in the crater.

Degradation in visual and radar visibility should be negligible because of the small amount of erosion and the fact that surface erosion begins shortly before touchdown. Potential damage to the spacecraft because of impact from erosion debris is not readily established. However, no damage was observed during any of the Surveyor landings or during the vernier engine erosion experiments on Surveyors V and VI. The evidence that is available concerning damage from debris impact suggests that the hazard is small. Some dust was believed to have adhered to the mirrors on Surveyor III, probably having been deposited during the non-nominal landing. On Surveyors V and VI no detectable degradation was observed in the spacecraft functional performance or in the thermal characteristics, although a few debris particles were deposited on top of the thermal compartments after vernier engine firings.

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